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AGARD ADVISORY REPORT No. 156

AGARD Two-Dimensional Aeroelastic Configurations

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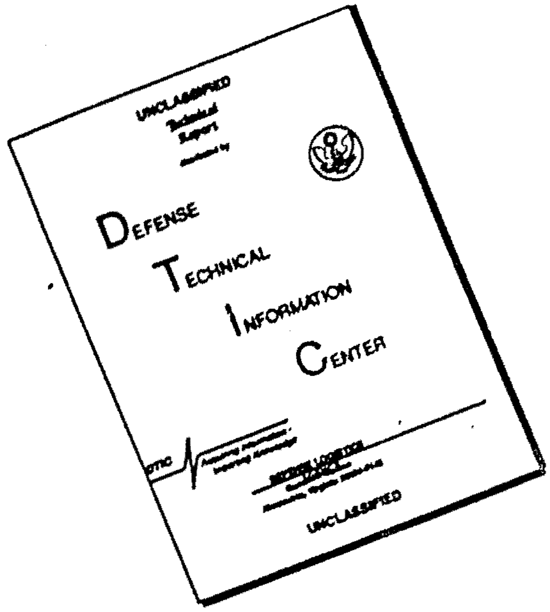

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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AGARD TWO-DIMENSIONAL AEROELASTIC CONFIGURATIONS.

compiled by

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This Advisory Report was sponsored by the Standard Aeroelastic Configurations Working Group of the Structures and Materials Panel. A further Advisory Report covering Three-Dimensional Configurations is planned for publication in early 1980.

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- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
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Published August 1979

ISBN 92-835-1333-9

Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London, W1P 1HD

PREFACE

At its Fall 1977 meeting in Voss, Norway the AGARD Structures and Materials Panel (SMP) formed a Working Group on "Standard Configurations for Aeroelastic Applications of Transonic Unsteady Aerodynamics". The members were:

S.R.Bland, United States (Coordinator)
F.O.Carta, United States
L.Chesta, Italy
R.Dat, France
H.Forsching, Federal Republic of Germany (Deputy Chairman)
H.C.Garner, United Kingdom
W.Geissler, Federal Republic of Germany
J.J.Olsen, United States (Chairman)
J.J.Philippe, France (Fluid Dynamics Panel Representative)
H.Tijdeman, Netherlands
J.C.Uselton, United States (Fluid Dynamics Panel Representative)

The aim of the Working Group was to accelerate the development of new theoretical, numerical and experimental techniques in transonic unsteady aerodynamics and their application to aeroelastic problems of aircraft loads, stability and flutter. The members from six nations obtained numerous suggestions from aeroelasticians and aerodynamicists in their countries and worked diligently to mold the recommendations into a number which was manageable, yet constituted a valid test of newly emerging capabilities. This report constitutes their first product, a standard set of two dimensional airfoils and aerodynamic conditions.

It is the hope of the SMP that this effort will focus the pertinent research activities of the NATO nations; conserve manpower, computer, wind tunnel, and flight test resources; and stimulate further developments.

JAMES J.OLSEN
Chairman, Working Group on
Standard Aeroelastic Configurations

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AGARD Two-Dimensional Aeroelastic Configurations

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SUMMARY

The aeroelastician needs reliable, efficient methods for the calculation of unsteady aerodynamic forces in the frequently critical transonic speed regime. The development of such methods can be enhanced by the availability of a limited number of test cases for the comparison of competing methods. This report contains such test cases. Geometric descriptions of seven, two-dimensional airfoils and suggested aerodynamic conditions for each are included.

LIST OF SYMBOLS

c	airfoil chord, m
f	oscillation frequency, Hz
h	plunge displacement in z-direction, m
h_o	plunge amplitude, m
k	reduced frequency, $\omega c/2V$
M	free stream Mach number
NA	not applicable
p	static pressure, N/m^2
Re	Reynolds number Vc/ν
t	time, s
V	free stream velocity, m/s
x	streamwise coordinate relative to leading edge, m
x_α	pitch axis location relative to leading edge, m
x_δ	flap axis location relative to leading edge, m
z	coordinate normal to free stream, positive up, m
α	angle of attack, deg
α'	pitch rate $d\alpha/d\tau$, deg per semichord length travelled
α_m	mean α, deg
α_o	dynamic pitch angle, deg
γ	ratio of specific heats
δ	flap angle, deg
δ_m	mean δ, deg
δ_o	dynamic flap angle, deg
ν	kinematic viscosity, m^2/s
ρ	free stream density, kg/m^3
τ	nondimensional time in semichord lengths travelled, $2Vt/c$
ω	angular frequency, $2\pi f$, rad/s

The coordinate system, force and moment definitions, and sign conventions are given in figure 2.

1. INTRODUCTION

The technology of transonic aerodynamics is currently undergoing rapid development. Significant progress is being made in the solution of the equations describing the unsteady motion of airfoils and wings in transonic flow. The availability of reliable and efficient computational methods will greatly enhance the ability of the analyst to predict the aeroelastic behavior of high speed aircraft. In general, the inherent nonlinearity of the flow equations for the transonic regime requires the use of the finite-difference or finite-element methods of the computational fluid dynamicist. These methods tend to be expensive to use, requiring both large computer storage and long machine time. The aeroelastician needs to examine many cases, both for analysis and for structural design optimization, and therefore is interested in the development of reliable, more approximate methods.

In order to compare and evaluate analytical methods involving various degrees of approximation, the AGARD Structures and Materials Panel has defined a limited set of test cases to be used in evaluating the competing methods. This activity should serve to stimulate cooperative research and to conserve resources by providing a common set of analytical problems. This report contains the recommended test cases for two-dimensional unsteady transonic flow. Detailed geometric descriptions are given for seven airfoils of thicknesses from 6.0 to 16.5% (shown in fig. 1): a biconvex parabolic arc airfoil, three symmetric conventional airfoils, and three cambered supercritical airfoils. The aerodynamic conditions, such as Mach number, mean angle of attack, and oscillation amplitude and frequency are also given. In some cases, experimental data have been published and are available for comparison. Recommendations are also made for uniformity in definitions and reporting to enhance the desired comparisons.

2. AIRFOIL GEOMETRY

Figure 1 shows the seven AGARD airfoils. Four have conventional, symmetric sections, and three have supercritical sections. The airfoils NACA 0012, NBB-A3, BO A1, and NLR 7301 are among those included in the steady flow data base compiled by the AGARD Fluid Dynamics Panel in reference 1. (The BO A1 airfoil is referred to as CAST 7 in the reference.) Tabulated airfoil ordinates for five of the airfoils are

given in tables 1 to 5. The other two airfoils have analytic definitions. Because of the sensitivity of transonic calculations to airfoil slopes (and curvature for some methods), care should be taken to ensure that interpolations of the geometric data are as smooth as possible. The use of low-order least-square polynomials or spline functions is recommended in most cases. For densely tabulated data, local finite difference forms may be satisfactory. Reference 2 gives a discussion of the airfoil description problem. In any case, explicit account should be taken of the square root behavior at the airfoil nose. Whatever airfoil description is actually used in the aerodynamic analysis, it should be carefully documented so that the calculations can be duplicated by other analysts.

Comments on each of the airfoils are given in the following subparagraphs. In the case of the supercritical airfoils, the ordinates are given in the coordinate system furnished by the designer; angle of attack is defined to be zero in this system. In each case the airfoil chord c is used as the reference length in the geometric definitions.

2.1 Parabolic arc

The 6% parabolic arc airfoil of unit chord is defined by the equation

$$z/c = \pm 0.12(x/c)(1-x/c)$$

2.2 NACA 64A006

The ordinates for the symmetric NACA 64A006 airfoil are given in table 1. The published ordinates of reference 3 (p. 354) have been augmented by eight new ordinates in the nose region. These additional points are taken from reference 2. The nose radius is 0.00246c.

2.3 NACA 64A010

The ordinates for the NASA Ames Research Center model of the NACA 64A010 airfoil are given in table 2. This model airfoil has an actual thickness of about 10.6%.

2.4 NACA 0012

The NACA 0012 airfoil of unit chord is described (ref. 3, p. 113) by the equation

$$z/c = \pm\, 0.6\left(0.2969\sqrt{x/c} - 0.126(x/c) - 0.3516(x/c)^2 + 0.2843(x/c)^3 - 0.1015(x/c)^4\right)$$

The nose radius is 0.015867c.

2.5 MBB-A3

The MBB-A3 airfoil ordinates are given in table 3. The data for this 8.9%-thick supercritical airfoil were furnished by Messerschmitt-Bölkow-Blohm (MBB). Nine additional points in the nose region have been taken from reference 2. The design conditions for this airfoil are Mach number of 0.765, angle of attack of 1.5°, and lift coefficient of 0.519. The nose radius is 0.0087c.

2.6 DO A1

The DO A1 airfoil ordinates are given in table 4. The data for this 11.8%-thick supercritical airfoil were furnished by Dornier. The airfoil design is described in references 4 and 5. The design conditions are Mach number of 0.76, angle of attack of zero, and lift coefficient of 0.573. The nose radius is 0.0115c.

2.7 NLR 7301

The ordinates for the NLR 7301 airfoil are given in table 5. The data for this 16.5%-thick supercritical airfoil were furnished by the Nationaal Lucht-en Ruimtevaartlaboratorium (NLR). The airfoil design is described in reference 6. The design conditions are Mach number of 0.721 and angle of attack of −0.19°.

3. ANALYTICAL TEST CASES

The aerodynamic conditions and the unsteady motions for each airfoil are given in tables 6 to 12. As is customary in the U.S., the reduced frequency k and corresponding nondimensional time τ use the semi-chord $c/2$ as reference length. An attempt has been made to cover a range of conditions for each class of airfoil while at the same time limiting the total number of cases. Nevertheless, there are a total of 81 cases given in the tables. In addition, it is recommended that calculations of the mean steady flow $(k = 0)$ be made for each of the unsteady flow conditions analyzed. Published experimental data exist for some of the cases given; in other cases, tests have recently been completed or are planned; and in other cases, it is unlikely that experimental data will be available.

The cases selected allow for a systematic variation of several parameters for each airfoil. However, the resulting large number of cases tends to limit the usefulness of this report in providing comparisons for analysts working independently of one another. For this reason, a subset of 15 cases, marked in the tables by an asterisk, has been chosen for priority analysis. These cases provide for the variation of one parameter (frequency, mode of motion, amplitude, Mach number, or Reynolds number) at a time.

The modes of motion are described as follows. For airfoil pitch about a mean angle of attack

$$\alpha(t) = \alpha_m + \alpha_o \sin \omega t$$

where each α is in degrees and $\omega t = 2kVt/c = k\tau$.

For the plunge mode

$$h(t) = h_o \sin \omega t$$

For the control surface mode

$$\delta(t) = \delta_m + \delta_o \sin \omega t$$

The ratio of specific heats γ should be 1.4 for air. In performing viscous flow calculations, the boundary layer transition point should be specified. In some cases this information is available with the published experimental data.

3.1 Parabolic arc

Analytical test cases for the 6% parabolic arc airfoil are listed in table 6. Several Mach numbers are given for $k = 0.2$ and several frequencies for $M = 0.8$. The Mach numbers include the nonsubsonic values $M = 1.0$ and 1.1. The frequencies cover a very large range--from $k = 0.02$ to $k = 5$. Both pitching and plunging modes of motion are included. In addition to calculations for $\gamma = 1.4$, calculations for $\gamma = 1.14$ (appropriate for Freon-12 in the NASA Langley Transonic Dynamics Tunnel) are of interest for the pitching airfoil (cases 1-9).

One additional case for the parabolic arc airfoil is that of the thickening-thinning airfoil of reference 7. The airfoil increases from zero to 10% thickness in 15-chord lengths of travel and then returns to zero thickness in another 15-chord lengths of travel. This is the only case included in this report in which no lift is generated and in which disturbances approach zero as time approaches infinity. The airfoil shape is given by

$$z/c = \begin{cases} 0 & \tau \leq 0 \\ \pm 0.2(x/c)(1-x/c)[1-T^3(10 - 15T + 6T^2)] & 0 < \tau < 60 \\ 0 & \tau \geq 60 \end{cases}$$

where $T = \left|1 - \frac{\tau}{30}\right|$

and $\tau = 2Vt/c$

The Mach number is 0.85.

3.2 NACA 64A006

The analytical cases for the NACA 64A006 airfoil are given in table 7. All cases are for the airfoil with flap oscillating about zero mean flap position and with zero angle of attack. Frequency variation is included at five Mach numbers in the range $0.80 \leq M \leq 0.96$ and also amplitude variation at two Mach numbers. Experimental results for these cases are reported in reference 6. Transition was fixed at $x/c = 0.1$ on upper and lower surfaces.

3.3 NACA 64A010

Analytical test cases for the NASA Ames model of the NACA 64A010 airfoil are listed in table 8. The cases were selected from an extensive set of measurements recently completed at the NASA Ames Research Center. Reference 8 presents a summary of these tests. In each case the pitch axis is at the quarter-chord and the mean angle of attack is zero. At $M = 0.8$ a range of frequency and two amplitudes and Reynolds numbers are given.

3.4 NACA 0012

The analytical cases for the NACA 0012 airfoil are given in table 9. The cases have been selected from free transition experiments subsequent to the preliminary results reported in reference 9. The first four cases are for pitch oscillation and, with helicopter interests in mind, include the only cases for a symmetric airfoil with sizable mean angles and oscillation amplitudes in this report. Case 4 is for oscillation amplitude $\alpha_o \to 0$, but a small value of $\alpha_o = 0.25$ may be taken if the analytical method requires it.

Cases 6 to 8 represent transient angle-of-attack changes at nominally constant pitch rates α' and are the only transient cases in the tables in this report. In the experiments the instrumentation cannot provide constant α' during the initial growth, and the measured time-dependent angles of attack are represented approximately by

$$\begin{array}{lll} \text{Case 6} & \alpha(\tau) = 0.0004825\ \tau^2(72-\tau) & 0 \leq \tau \leq 26.0 \\ \text{Case 7} & \alpha(\tau) = 0.0000023\ \tau^2(370-\tau) & 0 \leq \tau \leq 133.3 \\ \text{Case 8} & \alpha(\tau) = 0.0000519\ \tau^2(130-\tau) & 0 \leq \tau \leq 42.3 \end{array}$$

The upper limits of τ correspond to the upper limits of α and the final pitch rates $\alpha' = d\alpha/d\tau$ given in table 9.

3.5 MBB-A3

The analytical cases for the MBB-A3 supercritical airfoil are listed in table 10. The cases

selected represent variations in M and α_m about the design point ($M = 0.765$, $\alpha = 1.5^o$). Both pitch and plunge examples are included. In addition, frequency is varied up to $k = 0.9$ and, as for the parabolic arc, Mach numbers 0.9, 1.0, and 1.1 are included as a challenge to theoreticians. Experimental results are given in reference 10.

3.6 DO A1

Analytical cases for the DO A1 supercritical airfoil are given in table 11. Pitching oscillations for cases very near the design point ($M = 0.76$, $\alpha = 0^o$) were selected. Provision is made for variations of Reynolds number and of mean incidence in the range $-0.5^o \le \alpha_m \le 2.5^o$.

3.7 NLR 7301

The analytical cases for the NLR 7301 supercritical airfoil are listed in table 12. Three flow regimes are represented: subcritical flow ($M = 0.5$, $\alpha = 0.4^o$), flow with a strong shock wave ($M = 0.7$, $\alpha = 2^o$), and the design point ($M = 0.721$, $\alpha = -0.19^o$).

This airfoil has the distinctive pitch axis $x_\alpha = 0.4c$. The cases include two amplitudes of pitch oscillation and frequencies up to $k = 0.453$. In addition, there are five cases of flap oscillation in the same flow regimes. Experimental results are available in reference 6. Transition was fixed at $x/c = 0.3$ on both upper and lower surfaces.

4. RECOMMENDATIONS FOR REPORTING RESULTS

Although it is impossible to require a single uniform format for reporting results obtained from different analytical methods, as much uniformity as is practical will certainly enhance the comparisons between various investigations that this AGARD activity is designed to promote. In any case, we again urge that such details as sign conventions, units, and nondimensionalizing factors be clearly reported.

The recommended definitions and sign conventions for pressure, force, and moment coefficients are shown in figure 2. In comparing results from either different methods or from the same nonlinear method at different amplitudes, it is desirable to nondimensionalize further by dividing the pressure coefficient, say, by the amplitude. In this case, a symbol such as C_p/α_o should be used for the pressure coefficient per radian.

In unsteady aerodynamics the coefficients are, of course, functions of time. The aeroelastician has traditionally worked with complex coefficients for harmonic motion. These may be expressed as real (in-phase with the motion) and imaginary parts, or, alternatively, as magnitude and phase. For nonlinear aerodynamics, this representation is inadequate. In general, the coefficients are computed as functions of time. A Fourier analysis can be made and higher harmonics reported along with the fundamental. In many cases a spectral analysis may be more appropriate. In addition to pressure and force coefficients, the shock wave strength and position, and phase with respect to airfoil motion are important. A comparison of the mean values of all of the unsteady flow parameters with the corresponding parameters for the mean steady flow is also of interest.

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Table 1.- NACA 64A006

Upper surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.0000	0.00000	.0050	.00485	.2500	.02757	.6500	.02188
.0005	.00150	.0075	.00585	.3000	.02896	.7000	.01907
.0010	.00221	.0125	.00739	.3500	.02977	.7500	.01602
.0015	.00270	.0250	.01016	.4000	.02999	.8000	.01285
.0020	.00311	.0500	.01399	.4500	.02945	.8500	.00967
.0025	.00347	.0750	.01684	.5000	.02825	.9000	.00649
.0030	.00379	.1000	.01919	.5500	.02653	.9500	.00331
.0035	.00409	.1500	.02283	.6000	.02438	1.0000	.00013
.0040	.00435	.2000	.02557				

Lower surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.0000	0.00000	.0050	-.00485	.2500	-.02757	.6500	-.02188
.0005	-.00150	.0075	-.00585	.3000	-.02896	.7000	-.01907
.0010	-.00221	.0125	-.00739	.3500	-.02977	.7500	-.01602
.0015	-.00270	.0250	-.01016	.4000	-.02999	.8000	-.01285
.0020	-.00311	.0500	-.01399	.4500	-.02945	.8500	-.00967
.0025	-.00347	.0750	-.01684	.5000	-.02825	.9000	-.00649
.0030	-.00379	.1000	-.01919	.5500	-.02653	.9500	-.00331
.0035	-.00409	.1500	-.02283	.6000	-.02438	1.0000	-.00013
.0040	-.00435	.2000	-.02557				

Table 2.- NACA 64A010 (NASA Ames model)

Upper surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.00000	0.00000	.01798	.01573	.09002	.03213	.44999	.05226
.00102	.00420	.02200	.01722	.10003	.03369	.50003	.05000
.00198	.00562	.02601	.01854	.10998	.03515	.55001	.04681
.00300	.00701	.03002	.01976	.11999	.03653	.60000	.04287
.00401	.00809	.03399	.02086	.13000	.03787	.64999	.03833
.00498	.00893	.03800	.02188	.14001	.03912	.70003	.03334
.00605	.00972	.04201	.02287	.15001	.04030	.75001	.02805
.00701	.01037	.04602	.02378	.20000	.04526	.80000	.02267
.00798	.01096	.04999	.02464	.24999	.04894	.84999	.01725
.00899	.01156	.05999	.02673	.30003	.05149	.90003	.01180
.01001	.01212	.07000	.02864	.35001	.05298	.95001	.00640
.01402	.01409	.08001	.03041	.40908	.05307	1.00000	0.00000

Lower surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.00000	0.00000	.01798	-.01584	.09002	-.03220	.44999	-.05237
.00102	-.00338	.02200	-.01731	.10003	-.03375	.50003	-.05019
.00198	-.00501	.02601	-.01865	.10998	-.03516	.55001	-.04704
.00300	-.00634	.03002	-.01986	.11999	-.03654	.60000	-.04315
.00401	-.00708	.03399	-.02098	.13000	-.03783	.64999	-.03861
.00498	-.00850	.03800	-.02203	.14001	-.03901	.70003	-.03360
.00605	-.00946	.04201	-.02301	.15001	-.04010	.75001	-.02835
.00701	-.01020	.04602	-.02390	.20000	-.04502	.80000	-.02289
.00798	-.01086	.04999	-.02478	.24999	-.04870	.84999	-.01733
.00899	-.01151	.05999	-.02686	.30003	-.05139	.90003	-.01172
.01001	-.01210	.07000	-.02877	.35001	-.05292	.95001	-.00606
.01402	-.01415	.08001	-.03053	.40908	-.05321	1.00000	0.00000

Table 3.- MBB-A3

Upper surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.000000	.001500	.054097	.032227	.366582	.056673	.702965	.039399
.000050	.002500	.060767	.033591	.391880	.056830	.717314	.037662
.000350	.004260	.068097	.034989	.417129	.056777	.733063	.035670
.000650	.005370	.076146	.036410	.442428	.056506	.750412	.033343
.000950	.006280	.084996	.037845	.467677	.056013	.769512	.030770
.001250	.007000	.094745	.039311	.492925	.055292	.790510	.027815
.001550	.007670	.105445	.040801	.518224	.054325	.813559	.024525
.001850	.008260	.117284	.042310	.540973	.053240	.838950	.020919
.002150	.008780	.130193	.043832	.561422	.052086	.866357	.017418
.002550	.009472	.144463	.045359	.579871	.050902	.887206	.014354
.007550	.015109	.160142	.046888	.596420	.049720	.907805	.011651
.012549	.018601	.177391	.048397	.611369	.048553	.926304	.009265
.017549	.021270	.196390	.049876	.625019	.047400	.942053	.007258
.022549	.023440	.217239	.051303	.636868	.046351	.955402	.005573
.027549	.025270	.240038	.052651	.647768	.045327	.966752	.004149
.032548	.026859	.265487	.053913	.657567	.044366	.978101	.002730
.037548	.028279	.290785	.054931	.667317	.043368	.989451	.001314
.042548	.029573	.316036	.055725	.678116	.042219	1.000000	0.000000
.048048	.030887	.341333	.056305	.689966	.040904		

Lower surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.000000	.001500	.054097	-.012379	.366582	-.031514	.702965	-.014088
.000050	0.000000	.060767	-.012991	.391880	-.031667	.717314	-.013032
.000350	-.001200	.068097	-.013665	.417129	-.031539	.733063	-.011913
.000650	-.001810	.076146	-.014400	.442428	-.031117	.750412	-.010733
.000950	-.002270	.084996	-.015202	.467677	-.030391	.769512	-.009503
.001250	-.002600	.094745	-.016076	.492925	-.029352	.790510	-.008234
.001550	-.002900	.105445	-.017023	.518224	-.027997	.813559	-.006941
.001850	-.003150	.117284	-.018050	.540973	-.026549	.838950	-.005632
.002150	-.003380	.130193	-.019150	.561422	-.025106	.866357	-.004480
.002550	-.003676	.144463	-.020326	.579871	-.023724	.887206	-.003471
.007550	-.005750	.160142	-.021575	.596420	-.022443	.907805	-.002689
.012549	-.007000	.177391	-.022885	.611369	-.021268	.926304	-.002060
.017549	-.008040	.196390	-.024247	.625019	-.020187	.942053	-.001572
.022549	-.008880	.217239	-.025635	.636868	-.019246	.955402	-.001186
.027549	-.009590	.240038	-.027014	.647768	-.018380	.966752	-.000873
.032548	-.010218	.265487	-.028369	.657567	-.017603	.978101	-.000569
.037548	-.010775	.290785	-.029500	.667317	-.016834	.989451	-.000273
.042548	-.011289	.316036	-.030619	.678116	-.015980	1.000000	0.000000
.048048	-.011818	.341333	-.031094	.689966	-.015072		

Table 4.- DO A1

Upper surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.000000	0.000000	.035000	.032730	.335000	.067865	.755000	.046385
.000400	.003367	.047500	.037702	.395000	.068511	.815000	.036622
.001000	.005306	.065000	.043075	.455000	.068165	.875000	.025400
.002000	.007536	.087500	.048272	.515000	.066764	.920000	.016511
.003500	.010124	.115000	.053034	.575000	.064155	.950000	.010504
.005000	.012293	.155000	.058089	.635000	.060079	.977500	.004952
.007500	.015341	.215000	.063124	.695000	.054220	1.000000	.000353
.012500	.020110	.275000	.066167				

Lower surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
0.000000	0.000000	.017500	-.016627	.215000	-.046321	.695000	-.015660
.000400	-.003189	.025000	-.018526	.275000	-.049645	.755000	-.008096
.001000	-.005060	.035000	-.020850	.335000	-.050268	.815000	-.002087
.002000	-.007133	.047500	-.023626	.395000	-.048363	.875000	.001038
.003500	-.009271	.065000	-.027131	.455000	-.044306	.920000	.000787
.005000	-.010822	.087500	-.031022	.515000	-.038542	.950000	-.000627
.007500	-.012695	.115000	-.035181	.575000	-.031525	.977500	-.002626
.012500	-.015053	.155000	-.040398	.635000	-.023715	.999998	-.004655

Table 5.- NLR 7301

Upper surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
.0000012	-.0004100	.0511909	.0586888	.3506698	.0868880	.6846027	.0659158
.0002852	.0051408	.0558322	.0600098	.3596645	.0869741	.6915335	.0647960
.0005782	.0075616	.0604737	.0612182	.3686593	.0870330	.6987344	.0635875
.0008728	.0094526	.0651155	.0623327	.3776542	.0870609	.7059354	.0623078
.0011582	.0110534	.0697575	.0633680	.3866493	.0870576	.7131366	.0610781
.0014442	.0124442	.0752982	.0645125	.3958168	.0870223	.7203378	.0597789
.0017206	.0136850	.0796317	.0653752	.4049845	.0869547	.7279194	.0583806
.0019873	.0148157	.0836096	.0661284	.4141523	.0868548	.7355010	.0569518
.0022643	.0158465	.0874776	.0668324	.4233202	.0867220	.7430827	.0554945
.0025315	.0168173	.0912656	.0674974	.4320250	.0865674	.7506645	.0540098
.0027889	.0177180	.0952837	.0681786	.4407313	.0863827	.7587541	.0523972
.0041575	.0217220	.1013358	.0691618	.4494369	.0861683	.7668438	.0507569
.0055279	.0250359	.1073882	.0700970	.4581425	.0859239	.7749336	.0490906
.0068200	.0277496	.1150866	.0713095	.4657682	.0856051	.7830235	.0474003
.0080636	.0300732	.1206626	.0720014	.4733980	.0854226	.7918338	.0455342
.0093373	.0321969	.1274898	.0729627	.4810198	.0851362	.8006444	.0436440
.0105917	.0341309	.1351173	.0739758	.4886457	.0848253	.8094548	.0417320
.0118069	.0358180	.1429885	.0748193	.4950915	.0845432	.8182659	.0398007
.0129226	.0372772	.1508520	.0757161	.5015374	.0842451	.8280181	.0376441
.0139789	.0385702	.1595993	.0766549	.5079833	.0839246	.8377629	.0354699
.0150753	.0398035	.1683666	.0775817	.5144293	.0835874	.8475117	.0332812
.0161920	.0409766	.1731193	.0780035	.5223431	.0831474	.8572605	.0310812
.0172689	.0420432	.1802688	.0786689	.5302569	.0826778	.8672670	.0288147
.0182563	.0429644	.1874216	.0793026	.5355329	.0823680	.8772736	.0265433
.0191141	.0437226	.1927028	.0797509	.5442195	.0817743	.8872801	.0242793
.0199221	.0444002	.1979881	.0801829	.5529062	.0811616	.9000586	.0213713
.0208101	.0451044	.2032654	.0805993	.5601278	.0806215	.9100650	.0191086
.0220475	.0460222	.2085468	.0810003	.5673495	.0800522	.9200719	.0168971
.0236962	.0471471	.2143331	.0814224	.5734910	.0795444	.9300779	.0146213
.0251615	.0480686	.2201193	.0818268	.5796329	.0790140	.9444370	.0118493
.0261299	.0486353	.2259057	.0822139	.5849489	.0785361	.9492263	.0104032
.0270786	.0491572	.2316922	.0825862	.5902653	.0780403	.9540156	.0093643
.0271883	.0492156	.2380860	.0829741	.5949416	.0775888	.9588047	.0083341
.0272202	.0492368	.2444800	.0833463	.5996179	.0771227	.9635940	.0073137
.0275492	.0494030	.2508740	.0836953	.6038891	.0766839	.9683831	.0063045
.0277475	.0495076	.2572680	.0840272	.6081605	.0762325	.9731722	.0053076
.0281531	.0497145	.2643395	.0843728	.6160230	.0753675	.9779613	.0043282
.0286960	.0499059	.2714110	.0846961	.6234356	.0745111	.9827506	.0033558
.0292153	.0502401	.2784828	.0849974	.6305179	.0736551	.9849066	.0029250
.0295948	.0504226	.2855544	.0852771	.6373704	.0727918	.9870628	.0024974
.0299942	.0506142	.2933086	.0855593	.6441229	.0719073	.9892191	.0020730
.0305835	.0508944	.3010629	.0858161	.6507655	.0710047	.9913752	.0016520
.0312124	.0511906	.3088172	.0860480	.6574082	.0700648	.9935315	.0012342
.0326307	.0518452	.3165716	.0862555	.6641310	.0690932	.9956877	.0008195
.0372699	.0538378	.3250960	.0864557	.6709815	.0680654	.9978438	.0004082
.0419098	.0554298	.3336205	.0866269	.6778320	.0670059	1.0000000	0.0000009
.0465901	.0572348	.3421451	.0867696				

Table 5.- NLR 7301 (Continued)

Lower surface

x/c	z/c	x/c	z/c	x/c	z/c	x/c	z/c
.0000012	-.0004100	.0449476	-.0460334	.3107782	-.0757932	.7011672	-.0285353
.0002390	-.0055393	.0474028	-.0469776	.3207786	-.0758888	.7115156	-.0262375
.0004715	-.0076887	.0502579	-.0478767	.3307787	-.0759290	.7170096	-.0250220
.0007057	-.0089079	.0556900	-.0494775	.3408486	-.0759155	.7225036	-.0238100
.0009290	-.0100673	.0611217	-.0509508	.3508484	-.0758457	.7279977	-.0226052
.0011018	-.0110467	.0665532	-.0523143	.3608481	-.0757109	.7334917	-.0214062
.0013843	-.0119260	.0719863	-.0535893	.3708476	-.0755336	.7393630	-.0201338
.0016266	-.0127356	.0759493	-.0544637	.3808468	-.0752869	.7452344	-.0188724
.0017878	-.0131269	.0799142	-.0553045	.3908459	-.0749768	.7511058	-.0176240
.0018689	-.0135066	.0838791	-.0561107	.4008449	-.0746002	.7569772	-.0163907
.0021310	-.0142439	.0878439	-.0568850	.4108436	-.0741535	.7636408	-.0150119
.0024031	-.0149630	.0915458	-.0575815	.4208420	-.0736331	.7703044	-.0136501
.0031280	-.0166910	.0952477	-.0582561	.4308404	-.0730367	.7769680	-.0123323
.0038523	-.0181509	.0989497	-.0589080	.4408386	-.0723540	.7836318	-.0110377
.0045461	-.0194669	.1026515	-.0595325	.4525558	-.0714666	.7919873	-.0094628
.0051993	-.0206151	.1062731	-.0601275	.4617835	-.0706399	.8003429	-.0079460
.0058423	-.0216432	.1098948	-.0607023	.4674619	-.0701032	.8086987	-.0064930
.0065252	-.0226612	.1135166	-.0612573	.4783487	-.0689783	.8170548	-.0051070
.0072862	-.0236990	.1171380	-.0617936	.4859962	-.0681139	.8270502	-.0035437
.0081113	-.0247566	.1249661	-.0628505	.4926739	-.0673125	.8370460	-.0020917
.0089642	-.0257742	.1319939	-.0638686	.4991016	-.0665011	.8470422	-.0007601
.0098078	-.0267117	.1395768	-.0648552	.5056491	-.0656372	.8570388	.0004429
.0106595	-.0276093	.1471595	-.0657853	.5124264	-.0647085	.8631068	.0011158
.0115521	-.0285067	.1557673	-.0667768	.5195435	-.0636985	.8731840	.0020946
.0125668	-.0294462	.1643750	-.0677066	.5271003	-.0625883	.8831816	.0029266
.0137878	-.0305031	.1729825	-.0685721	.5350260	-.0613843	.8931796	.0036056
.0152312	-.0316596	.1815898	-.0693827	.5433830	-.0600725	.9031781	.0041258
.0168364	-.0324502	.1866811	-.0698360	.5462317	-.0596156	.9131771	.0044822
.0176813	-.0334455	.1917726	-.0702707	.5551425	-.0581517	.9231766	.0046702
.0185279	-.0340206	.1968636	-.0706871	.5640932	-.0566411	.9331765	.0046852
.0194747	-.0346411	.2019548	-.0710859	.5730235	-.0550136	.9431770	.0045232
.0204215	-.0352389	.2078710	-.0715271	.5827536	-.0533361	.9531780	.0041809
.0216085	-.0359586	.2137872	-.0719469	.5920886	-.0516075	.9601890	.0038317
.0227956	-.0366476	.2197036	-.0723400	.6014235	-.0498296	.9691707	.0032499
.0241816	-.0374166	.2256196	-.0727127	.6104285	-.0480676	.9736617	.0029000
.0255678	-.0381520	.2327707	-.0731341	.6194332	-.0462616	.9781528	.0025124
.0266913	-.0386255	.2399218	-.0735260	.6280382	-.0444919	.9822076	.0021267
.0291700	-.0399208	.2470728	-.0738833	.6366829	-.0426066	.9849110	.0018492
.0319445	-.0411455	.2542238	-.0742125	.6452277	-.0408666	.9876143	.0015550
.0339957	-.0418978	.2633623	-.0745898	.6537724	-.0390207	.9889660	.0014018
.0353428	-.0426210	.2725007	-.0749195	.6626960	-.0370703	.9922171	.0010162
.0370898	-.0433178	.2816391	-.0752020	.6716211	-.0351027	.9954683	.0006056
.0380367	-.0439892	.2907772	-.0754377	.6812200	-.0329730	.9991797	.0001112
.0416922	-.0450389	.3007770	-.0756429	.6908180	-.0308386	1.0000000	0.0000000

Table 6.- 6% parabolic arc

Case	M	α_o	h_o/c	k
1	0.7	0.5	0	0.2
2	0.8	0.5	0	0.02
3*	0.8	0.5	0	0.2
4	0.8	0.5	0	0.5
5	0.8	0.5	0	1.0
6	0.8	0.5	0	5.0
7	0.9	0.5	0	0.2
8	1.0	0.5	0	0.2
9	1.1	0.5	0	0.2
10	0.7	0	0.01	0.2
11*	0.8	0	0.01	0.2
12	0.9	0	0.01	0.2

Note: $\alpha_m = 0$, $x_\alpha/c = 0.25$, additional cases are in paragraph 3.1

Table 7.- NACA 64A006

Case	M	δ_o	f	k
1	0.800	1	30	0.064
2	0.800	1	120	0.254
3	0.825	1	30	0.062
4	0.825	2	30	0.062
5	0.825	1	120	0.248
6	0.850	1	30	0.060
7	0.850	1	120	0.242
8*	0.875	1	30	0.059
9*	0.875	2	30	0.059
10*	0.875	1	120	0.239
11	0.960	1	30	0.056
12	0.960	1	120	0.217

Note: $\alpha_m = \alpha_o = \delta_m = 0$, $x_\delta/c = 0.75$, $Re = 2.4 \times 10^6$

Table 8.- NACA 64A010

Case	M	ReX10^{-6}	α_o	f	k
1	0.498	2.5	0.96	10.8	0.100
2	0.502	10.0	1.02	10.8	0.100
3	0.796	12.5	1.03	4.2	0.025
4	0.796	12.5	1.02	8.6	0.051
5	0.796	12.5	1.02	17.2	0.101
6*	0.796	12.5	1.01	34.4	0.202
7	0.796	12.5	0.99	51.5	0.303
8	0.796	12.5	0.51	17.1	0.101
9	0.797	12.5	2.00	17.2	0.101
10*	0.802	3.4	0.96	33.2	0.200

Note: $\alpha_m = 0$, $x_\alpha/c = 0.25$

Table 9.- NACA 0012

Case	M	V	ReX10^{-6}	α_m	α_o	α'	f	k
1*	0.601	197	4.8	2.89	2.41	NA	50	0.081
2	0.599	197	4.8	3.16	4.59	NA	50	0.081
3	0.599	197	4.8	4.86	2.44	NA	50	0.081
4	0.755	263	5.5	0.02	~0	NA	62	0.081
5	0.755	263	5.5	0.02	2.51	NA	62	0.081
6	0.292	96	2.6	NA	0→15	0.03	NA	NA
7	0.600	191	4.6	NA	0→10	0.11	NA	NA
8*	0.606	196	4.7	NA	0→10	0.30	NA	NA

Note: $x_\alpha/c = 0.25$, final α' is given (see paragraph 3.4)

Table 10.- MBB-A3

Case	M	α_m	α_o	h_o/c	k
1	0.700	1.5	0.5	0	0.1
2	0.765	0.5	0.5	0	0.1
3*	0.765	1.5	0.5	0	0.1
4	0.765	1.5	0.5	0	0.3
5	0.765	1.5	0.5	0	0.9
6	0.765	2.0	0.5	0	0.1
7*	0.780	1.5	0.5	0	0.1
8	0.900	1.5	0.5	0	0.1
9	1.000	1.5	0.5	0	0.1
10	1.100	1.5	0.5	0	0.1
11	0.765	1.5	0	0.01	0.1
12	0.765	1.5	0	0.01	0.3
13	0.765	1.5	0	0.01	0.9

Note: $x_\alpha/c = 0.25$, $Re = 6X10^6$

Table 11.- DO A1

Case	M	ReX10^{-6}	α_m	α_o	k
1	0.70	6	0.0	0.5	0.2
2	0.74	6	0.0	0.5	0.2
3	0.76	6	-0.5	0.5	0.2
4*	0.76	6	0.0	0.5	0.2
5	0.76	6	0.0	1.0	0.2
6	0.76	3	0.5	0.5	0.2
7	0.76	6	0.5	0.5	0.2
8*	0.76	6	1.5	0.5	0.2
9	0.76	6	2.5	0.5	0.2
10	0.76	12	0.0	0.5	0.2
11	0.76	12	0.5	0.5	0.2
12	0.78	6	0.0	0.5	0.2

Note: $x_\alpha/c = 0.25$

Table 12.- NLR 7301

Case	M	α_m	α_o	δ_o	f	k
1	0.500	0.40	0.5	0	30	0.098
2	0.500	0.40	0.5	0	80	0.263
3	0.700	2.00	0.5	0	30	0.072
4	0.700	2.00	1.0	0	30	0.072
5	0.700	2.00	0.5	0	80	0.192
6	0.721	-0.19	0.5	0	30	0.068
7	0.721	-0.19	1.0	0	30	0.068
8*	0.721	-0.19	0.5	0	80	0.181
9	0.721	-0.19	0.5	0	200	0.453
10	0.500	0.40	0	1	30	0.098
11	0.700	2.00	0	1	30	0.072
12	0.721	-0.19	0	1	30	0.068
13*	0.721	-0.19	0	1	80	0.181
14	0.721	-0.19	0	1	200	0.453

Note: $x_\alpha/c = 0.4$, $x_\delta/c = 0.75$, $\delta_m = 0$

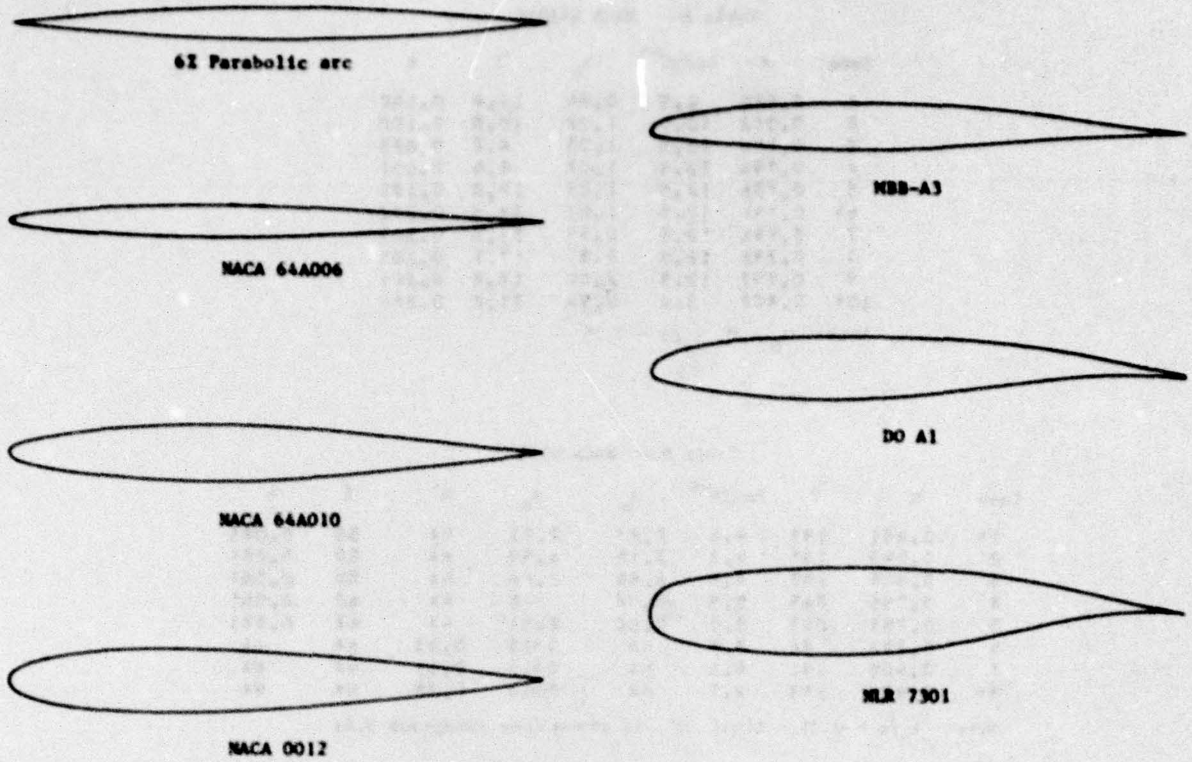
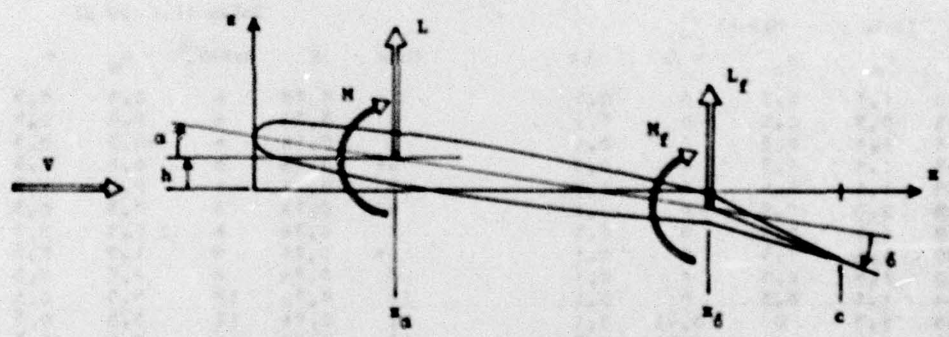


Figure 1.- AGARD Standard airfoils.



$q = \frac{1}{2}\rho V^2$ $\qquad C_p = \dfrac{p - p_\infty}{q}$ $\qquad \Delta C_p = C_{p,lower} - C_{p,upper}$

$L = qcc_l$ $\qquad L_f = qcc_{l,f}$

$M = qc^2c_m$ $\qquad M_f = qc^2c_h$

$$c_l = \oint_{airfoil} C_p d(x/c) = \int_0^1 \Delta C_p d(x/c)$$

$$c_m = \oint_{airfoil} C_p(x_\alpha/c - x/c - z/c \cdot dz/dx) d(x/c) = \int_0^1 \Delta C_p(x_\alpha/c - x/c) d(x/c)$$

$$c_{l,f} = \oint_{flap} C_p d(x/c) = \int_{x_\delta/c}^1 \Delta C_p d(x/c)$$

$$c_h = \oint_{flap} C_p(x_\delta/c - x/c - z/c \cdot dz/dx) d(x/c) = \int_{x_\delta/c}^1 \Delta C_p(x_\delta/c - x/c) d(x/c)$$

Figure 2.- Airfoil force and moment definitions.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AR-156	ISBN 92-835-1333-9	UNCLASSIFIED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title

AGARD TWO-DIMENSIONAL AEROELASTIC CONFIGURATIONS

7. Presented at

8. Author(s)/Editor(s)	9. Date
S.R.Bland	August 1979

10. Author's/Editor's Address	11. Pages
National Aeronautics and Space Administration Langley Research Center Hampton, VA 23665, USA	16

12. Distribution Statement This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Airfoils	Aeroelasticity
Aerodynamic configurations	Two-dimensional flow
Aerodynamic forces	Unsteady flow
Transonic flow	Applications of mathematics

14. Abstract

The aeroelastician needs reliable, efficient methods for the calculation of unsteady aerodynamic forces in the frequently critical transonic speed regime. The development of such methods can be enhanced by the availability of a limited number of test cases for the comparison of competing methods. This report contains such test cases. Geometric descriptions of seven, two-dimensional airfoils and suggested aerodynamic conditions for each are included.

This Advisory Report was sponsored by the Standard Aeroelastic Configurations Working Group of the Structures and Materials Panel. A further Advisory Report covering Three-Dimensional Configurations is planned for publication in early 1980.

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